Regional Stratification and Shear of the Various Streams Feeding the Philippine Straits

Arnold L. Gordon
Lamont-Doherty Earth Observatory
61 Route 9W
Palisades, NY 10964-8000
tele: 845 365-8325
fax: 845 365-8157
agordon@ldeo.columbia.edu

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http://www.satlab.hawaii.edu/onr/mindoro/wiki/index.php?n=Main.HomePage

LONG-TERM GOALS

The Analysis of in situ and satellite data with model output to investigate the stratification and shear of the Philippine seas at sub-meso to meso-scales to regional scales, so as to understand their relationship to the larger scale ocean and monsoon forcing. This work contributes to the “Characterization and Modeling of Archipelago Strait Dynamics” DRI [PhilEx] goal: to enhance our understanding of the oceanographic processes and features arising in and around straits, and improve our capability to predict the inherent spatial and temporal variability of these regions using models and advanced data assimilation techniques.

OBJECTIVES

To resolve the circulation and mixing within the Philippine Archipelago and neighboring seas [South China Sea, Sulu Sea and boundary with the open Pacific Ocean]. Features and processes of particular interest are those associated with the interaction of the mean and tidal currents with the strong seasonal forcing at regional and smaller scales, including the effects of the complex topography characteristic, passage constrictions and topographic sills of the Archipelago; the interaction of the interior seas of the Philippine Archipelago [Mindanao and Sibuyan Seas] with the larger scale dynamics; dense ‘ventilating’ overflow into isolated deep basins; the response of the circulation to highly textures wind stress curl patterns induced by the Archipelago configuration.

APPROACH

The stratification and circulation is revealed through an array of CTD/Lowered ADCP stations, as well as underway data [notably the hull mounted ADCP, SST/SSS and surface chlorophyll] collected during the field phase of PhilEx: Exploratory Cruise, June 2007; Regional IOP-08, January 2008; and Regional IOP-09, March 2009, as well as during the Joint Cruise of November/December 2007. These data are integrated with other observational data, including satellite sensing, moored instrumentation and model output, as needed to meet the DRI objectives. I collaborate with other DRI observationalists: Amy Ffield, Earth and Space Research: LADCP; Pierre Flament, University of

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Hawaii at Manoa: High frequency radio; Craig Lee, University of Washington: towed vehicles and Gliders; James Girton: EM profilers; Janet Sprintall, Scripps Institution of Oceanography: ADCP moorings; and Cesar Villanoy and Laura David, both at the Institute of Marine Research at the University of the Philippines: biochemical data. The model collaboration is accomplished via H. Hurlburt, J. Metzger, W. Han, J. Levin, B. Zhang, H. Arango, J. Doyle, P. May, J. Pullen and P. Lermusiaux.

WORK COMPLETED

Here are 5 physical oceanographic regional scale topics, led by A. Gordon, in various stages of completion. These were presented at the PhilEx All-Hands meeting in Honolulu in August 2009:

1. "Introduction to the Philippine archipelago-scale flow".

The southeast Asia Seas, with strong monsoons, inter-sea & interocean exchange, tides; all amidst a multitude of isolated deep basins with a network of interconnecting straits represent an oceanographic challenge to both observe and model. Research questions that are 'front-and-center' in our PhilEx research are:

§ How does the archipelago interior [stratification, velocity/transport] respond to remote and local forcing?

§ What are the dominant physical and dynamical balances that characterize the flow & mixing at different locations and scales within the Philippine Archipelago?

§ How well do models simulate the observed characteristics?

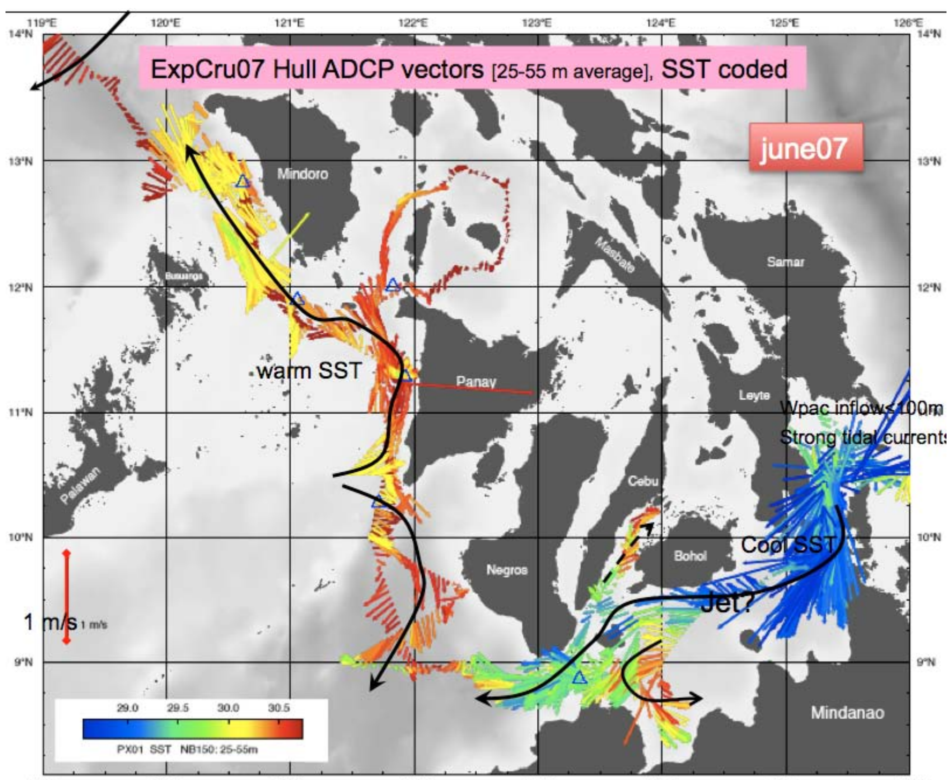
To advance these topics we are developing a full description of the circulation and stratification within the Philippine seas as observed by CTD/LADCP and the ship underway data recording system. This includes the similarities and differences observed in the PhilEx cruises, with reference to the changing atmospheric forcing.

The flow within the Philippine Seas (surface layer flow shown in Figure 1) is highly textures by the wind curl, complex geography and submarine morphology, as well as by the varied states within the South China Sea and western Pacific. The 2008 RIOP period experienced stronger and more variable wind forcing. Additionally, RIOP08 occurred during the wettest winter in over 30 years. June07/Jan08 surface density was only $\Delta\sigma$~+0.5 [Jan density > June density]. Normally the surface water in January density would be $\Delta\sigma$ +1.0 > June. Did the extra rain in 08 make for a stronger upper pycnocline? Did this affect water column shear?

We are investigating the interchange of Philippines waters with the South China Sea via Mindoro and Panay straits; and with the western Pacific waters via San Bernardino Strait and Surigao Strait, both of which experience strong tidal currents.

We find the Mindoro/Panay exchange depends on depth, with the mean flow towards the South China Sea in the upper ~100 m; towards Sulu Sea at deeper levels, with flow reversal occurring near 150 m; the strong southward flow is observed below ~450 m, which feeds the deep ventilation of the Sulu Sea.

We find near zero throughflow within the very tidal activity San Bernardino Strait but within Surigao Strait there may be substantial flow into the Mindanao Seas, ~0.2 to 0.4 Sv. The PhilEx salinity data within the San Bernardino and Surigao Straits indicate the likelihood of Pacific thermocline upwelling drawn from 100-200 meters, spreading on to the eastern shelf of the Philippines.



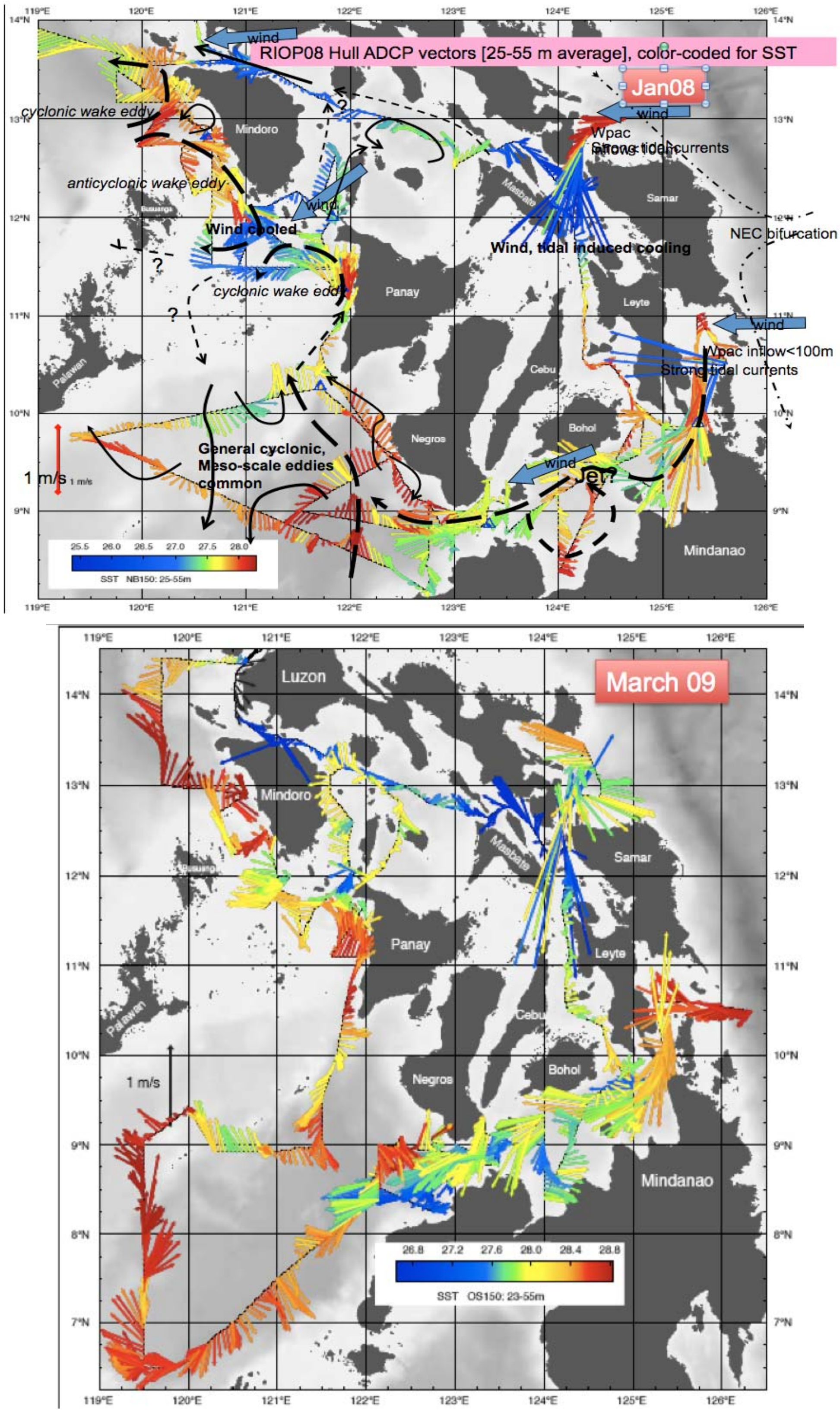


Figure 1: the surface layer 25-55 m vectors color coded for Sea Surface Temperature (SST) for the three PhilEx cruises.

2. "Mindoro/Panay Strait circulation and stratification"

Tessler, Gordon, Pratt, Sprintall: Panay Sill Overflow Dynamics. Submission to J. Phys. Oceanogr., in October 2009:

Strong overflow currents were observed at Panay Sill, in the Philippine Seas, using CTD, lowered ADCP, and a moored ADCP deployment between June 2007 and March 2009 (figure 2). The Panay Sill overflow water is part of the South China Sea Throughflow and derives from 400 m South China Sea water. Downstream it does not reach the deep Sulu Sea, but rather descends to 1250 m, settling above high-salinity deep water. Temporal means show velocities greater than 75 cm s^{-1} at 50 m above the bottom. Empirical orthogonal function analysis of the mooring time series shows the bottom overflow current dominates the flow with little seasonal variance. Weaker currents in the overlying water are seasonal in nature. Both the mean observed overflow transport and a hydraulic control model using hydrography at the sill measure a transport of 0.32 Sv. Analysis of Froude number variation across the sill shows the flow is hydraulically controlled. Thorpe-scale estimates of eddy diffusivity suggest mixing as high at 10^{-2} m^2s^{-1} just downstream of the supercritical to subcritical flow transition, suggesting a hydraulic jump downstream of the sill. The observed transport was used to calculate bulk diapycnal diffusivity in the Sulu Sea of 4.4 x 10^{-4} m^2s^{-1}.

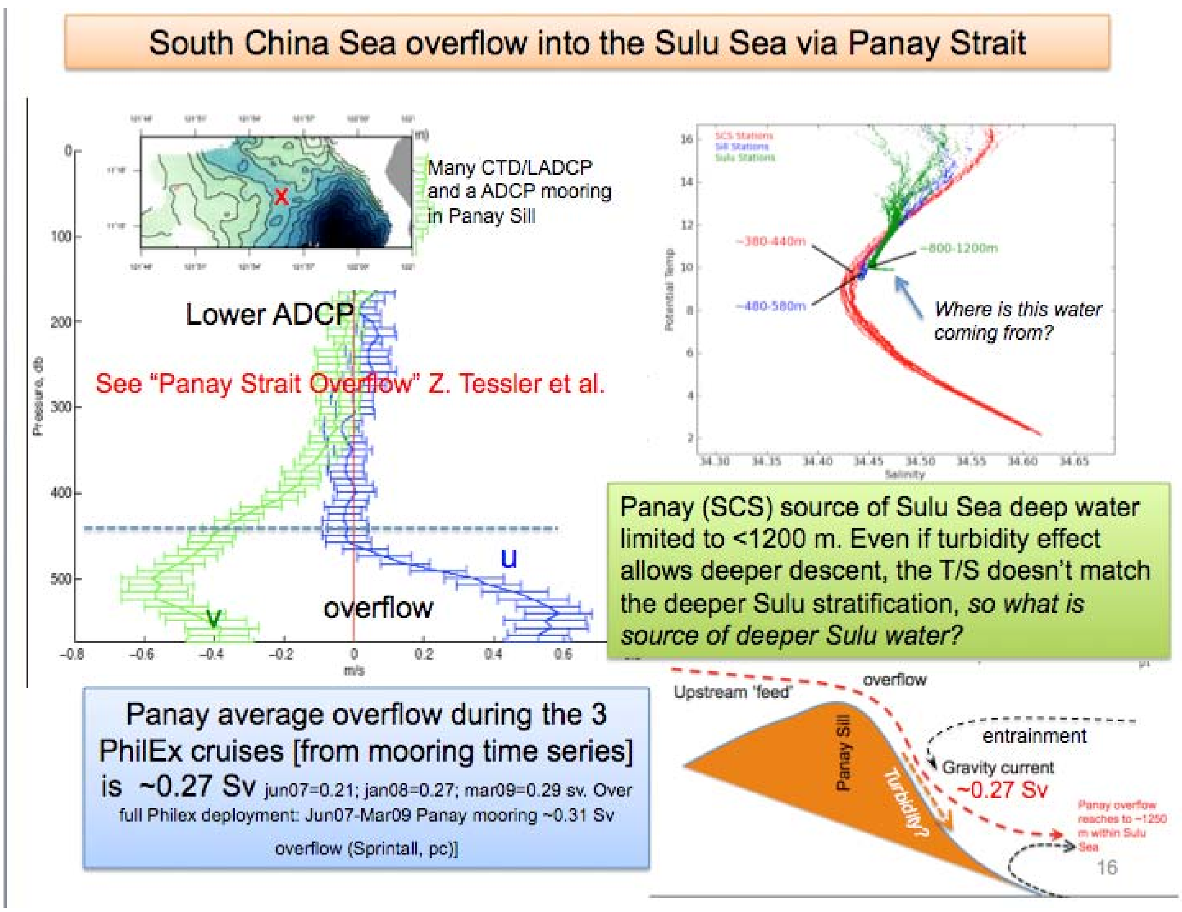


Figure 2 South China Sea water overflow into the Sulu Sea via the Panay Strait.

Summary:

- Strong diurnal-tide dominated overflow current, characterized by higher velocities, different direction, lower temperature, and lower salinity than overlying water

- Overflow water derived from 400 m South China Sea water and descends to approximately 1250 m, overlying high-salinity Sulu Sea deep water.

- Mean transport of 0:2 to 0:3 Sv across Panay Sill

- Froude number is greater than 1 at sill; diffusivities of up to 10^{-2} m^2s^{-1} just downstream of sill are suggested.

- Overflow likely to be enhanced during El Niño by ~1/3. Potential shutdown during La Niña.

3. “Circulation, stratification & ventilation of the Sulu Sea”

Presented at MOCA-09 July 2009, Montréal, CA:

‘Competing Overflows into the Deep Sulu Sea’ A. L. Gordon, Z. Tessler

The Sulu Sea lies within a 5 km deep basin, isolated from the neighboring ocean below 570 m. The deep Sulu Sea Theta°C is nearly isothermal, with a slight T-min at 2800 m. Below 1200 m is a marked salinity increase with depth (Figure 2). A single overflow source would induce a homogeneous volume within the deep Sulu Sea. The deep ventilation source is believed to be South China Sea water overflowing a 570 m sill in Panay Strait. The overflow amounts to 0.3 Sv of 9.67°C and 34.44 salinity water. The Sulu bottom water is 9.8°C and 34.472. To match the Sulu Sea bottom salinity the Panay Strait overflow would have to be much warmer than 9.8°C. The Sulu T/S profile indicates that Panay overflow reaches only to 1200 m, and cannot the sole source of Sulu Sea deep ventilation. The densest component is derived from overflow from the Sulawesi Sea, via the Sibutu Passage, sill of 300 m. There a mix of Sulawesi water from 200 to 400 m is required (Figure 3). We hypothesis that this overflow is achieved in ‘bursts’ in the tidal active Sibutu Passage [source of Sulu Sea Solitons]. The Sulawesi overflow oxygen is 2.2 ml/l. The deep oxy in Sulu is 0.85 ml/l. Using the 1996-2002 decease of deep Sulu oxygen of 0.026 ml/l, the residence time of the deep Sulu Sea is 50 years (Figure 4). We hypothesize that the deep Sulu Sea has competing overflows, which change in their relative importance with ENSO and longer periods.

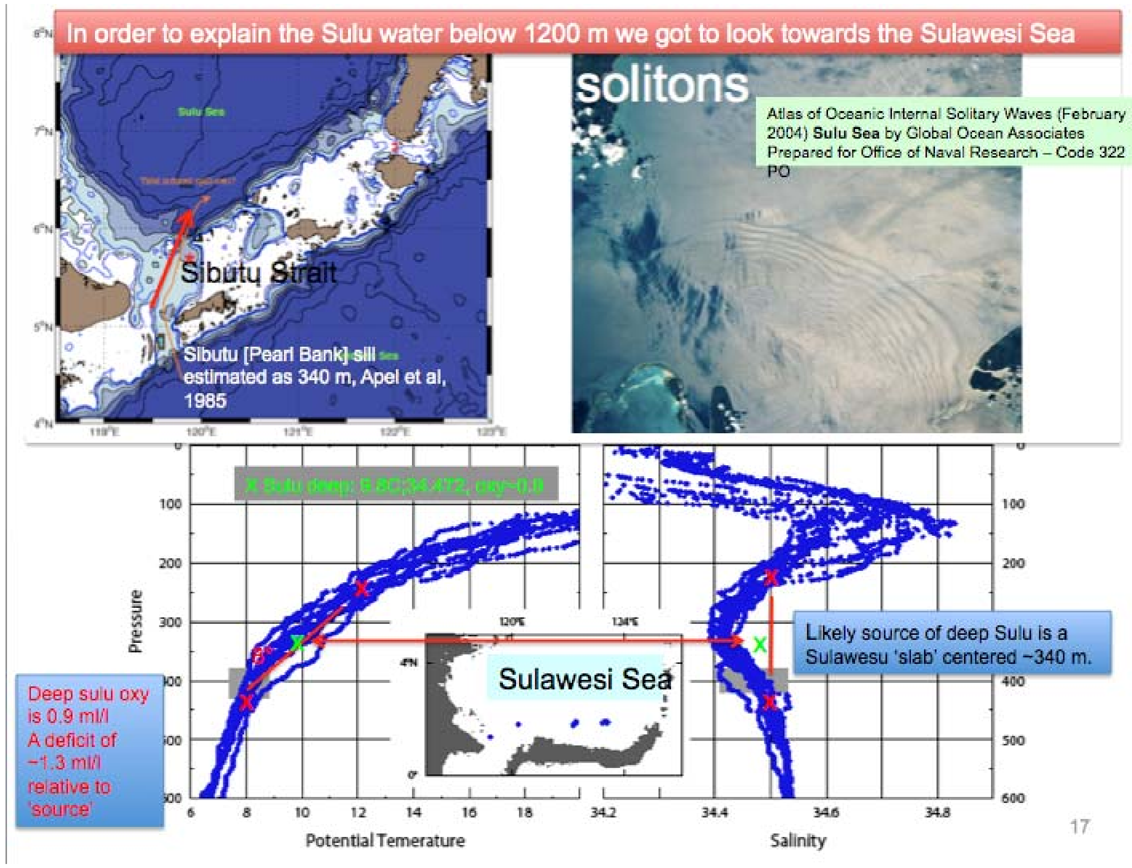


Figure 3: The likely source of the relatively saline water below 1250 m within the Sulu Sea [see figure 2] is overflow across the Sibutu Passage connecting the Sulawesi Sea to the southern Sulu Sea.

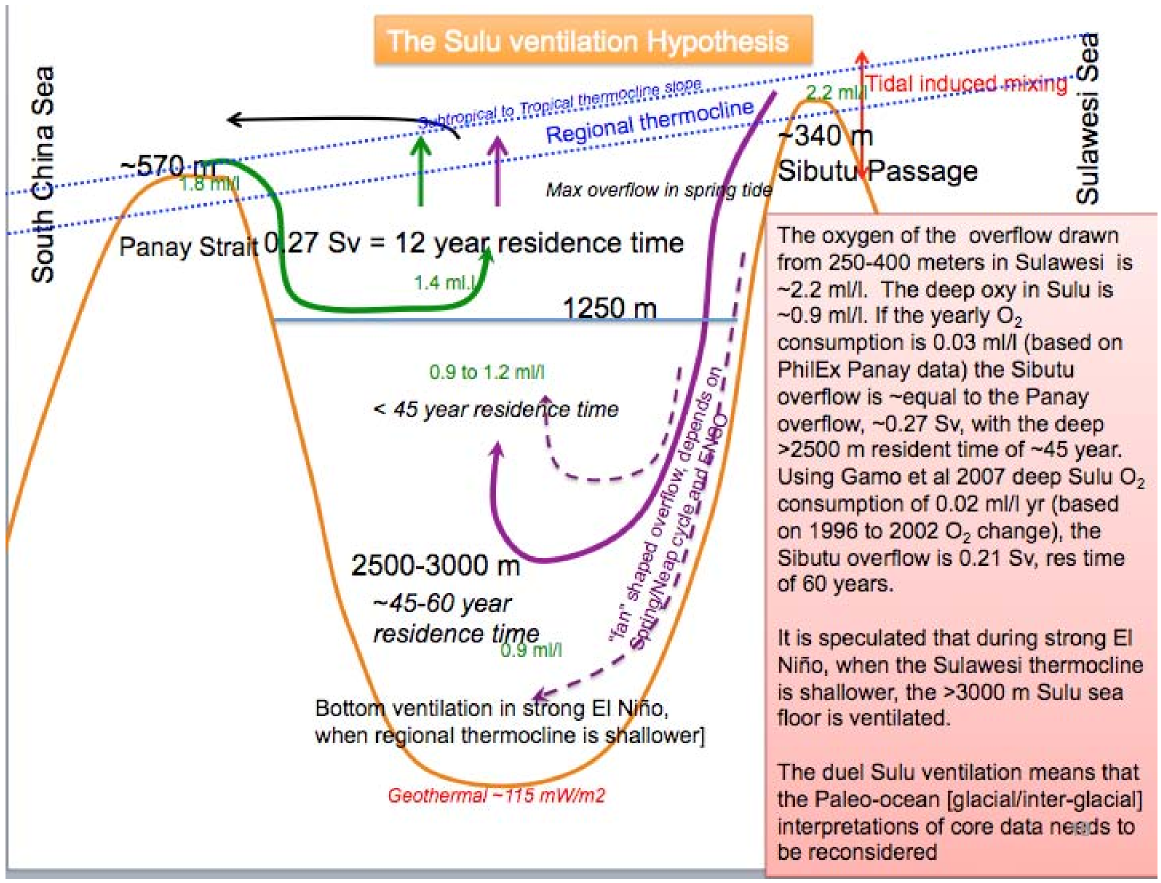


Figure 4 Schematic of the deep water ventilation of the Sulu Sea.

4. "Circulation, stratification & ventilation of the Mindanao [Bohol] Sea; Iligan Bay Eddy; and Dipolog Strait'

The surface layer circulation within the Mindanao (Bohol) Sea (Figure 5), reveals strong westward flow, dubbed the Mindanao Jet, along the northern boundary of the sea. This is fed from the Surigao Strait throughflow and by upwelling of the shallow estuary overturning characteristics of the Mindanao Sea (Figures 6, 7). The Mindanao Jet flows into the Sulu Sea. To the south of the Mindanao Jet, near 124°E is a persistent cyclonic flowing circulation cell, dubbed the Iligan Bay Eddy. This feature may be the consequence of upwelling from the deeper overturning circulation cell fed by dense water overflow in Dipolog Strait (Figure 7).

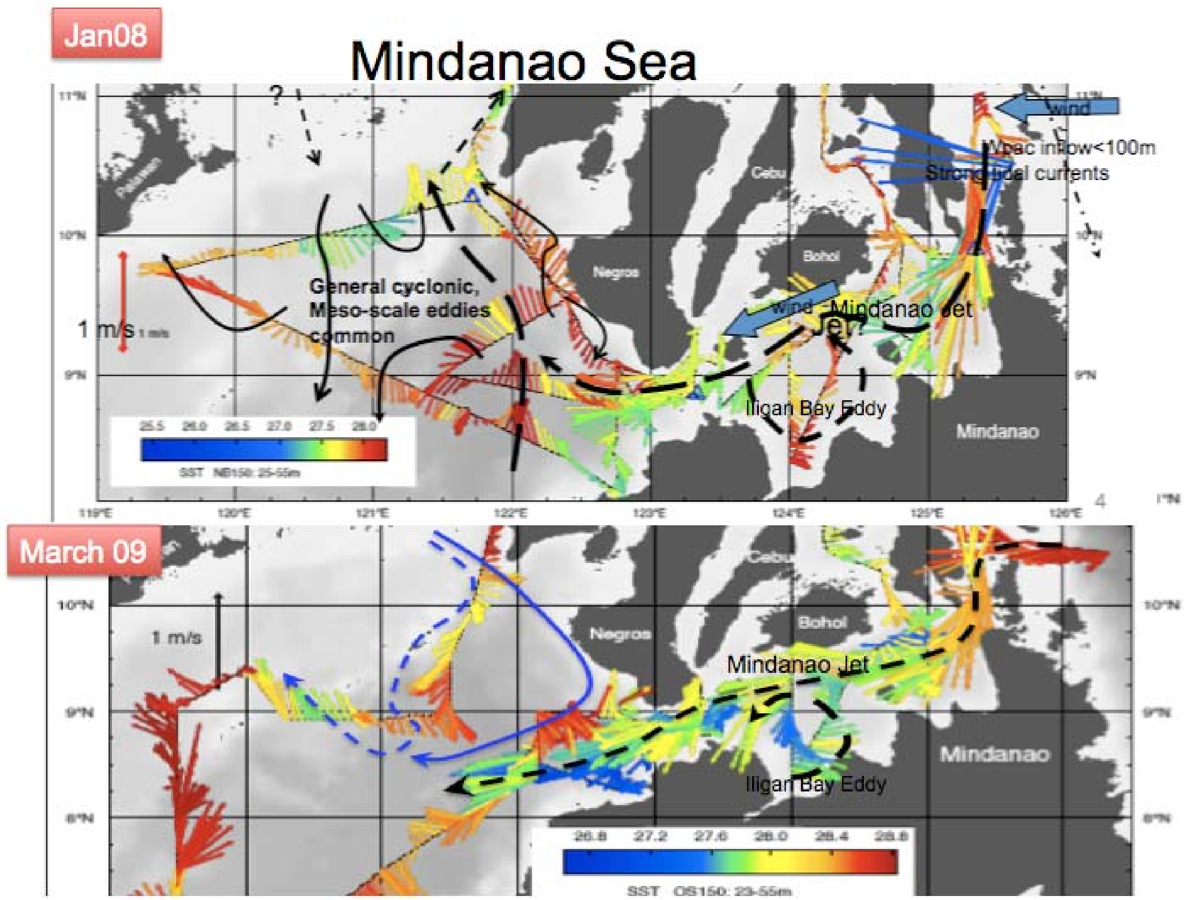


Figure 5 Surface layer vectors, color coded for SST in the Mindanao Sea and Sulu Sea for the 2008 and 2009 IOP PhilEx cruises.

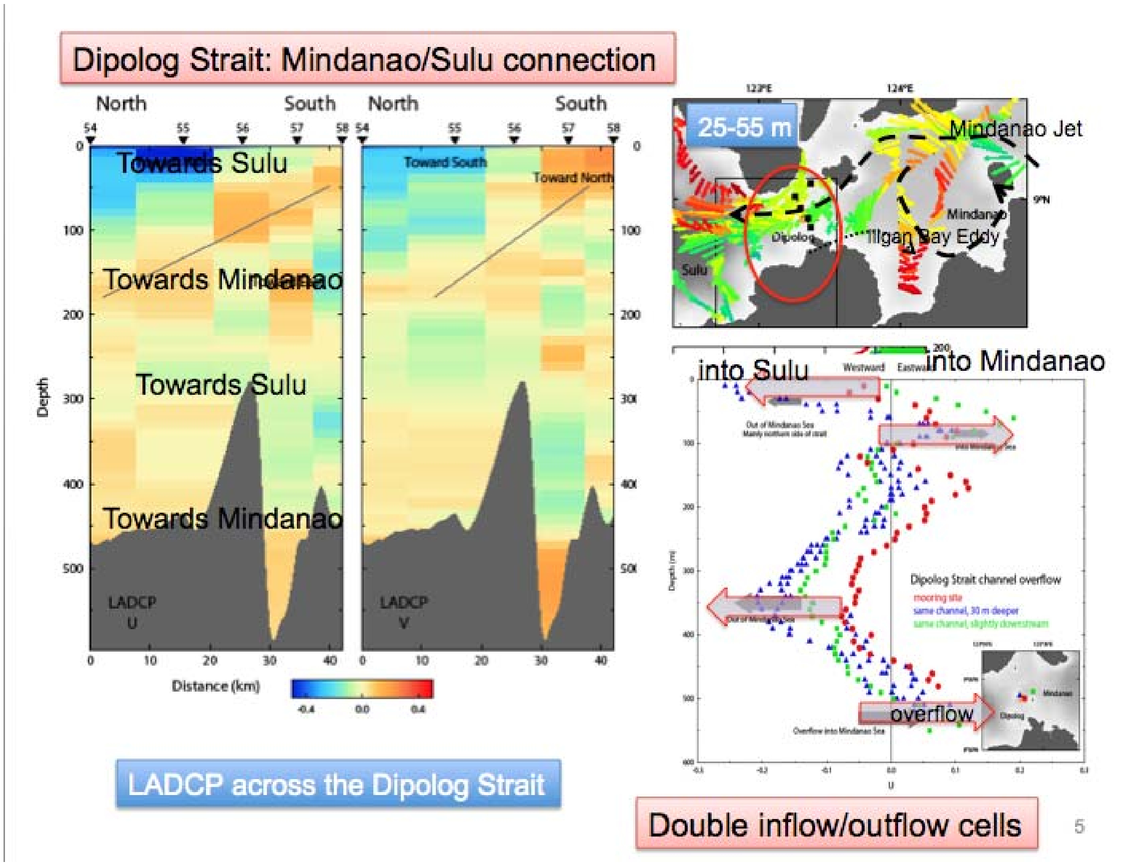


Figure 6 The shear within Dipolog Strait, the connection between the Mindanao (Bohol) Sea and the Sulu Sea. A schematic of the associate double estuary pattern of overturning within the Mindanao Sea is shown in Figure 7.

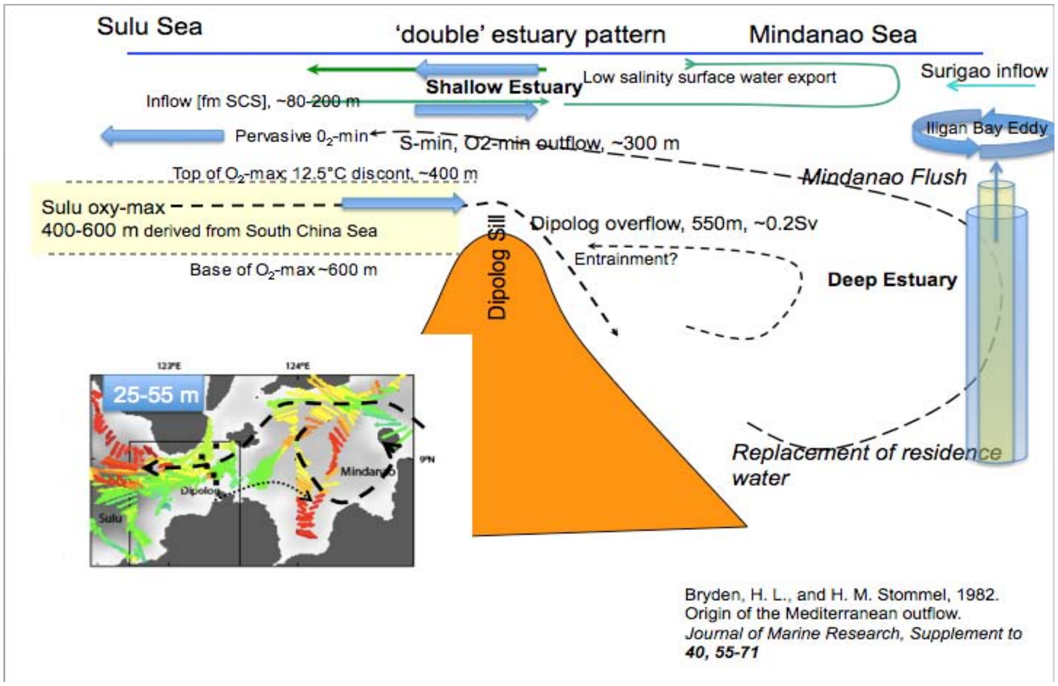


Figure 7: Schematic of the overflow patterns in the Mindanao (Bohol) Sea.

5. Gordon, A.L., Chris Jackson, Debra Tillinger, Zach Tessler, Andreas Thurnherr: Sulutons [Sulu Sea Solitons]

As we approached the southwestern position within the Sulu Sea we were fortunate to be at the right spot [Apel's station SS2] at the right time new moon on 12 March 2009, to record the passage of Solitons, characteristic of the Sulu Sea (figure 8 and 9).

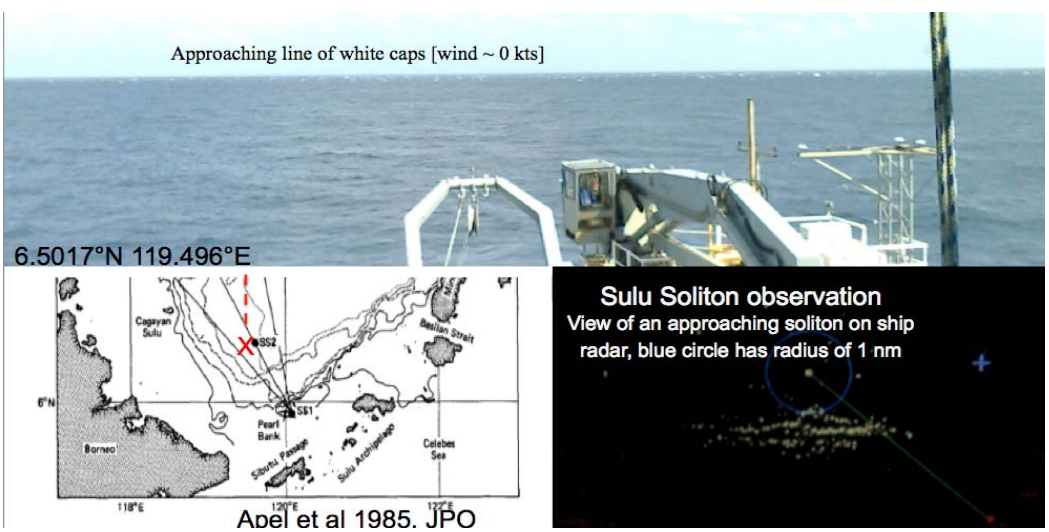


Figure 8, Soliton approaches, ~3 pm local, 12 March 2009 (GMT Day 12.3). Ship radar image lower right panel.

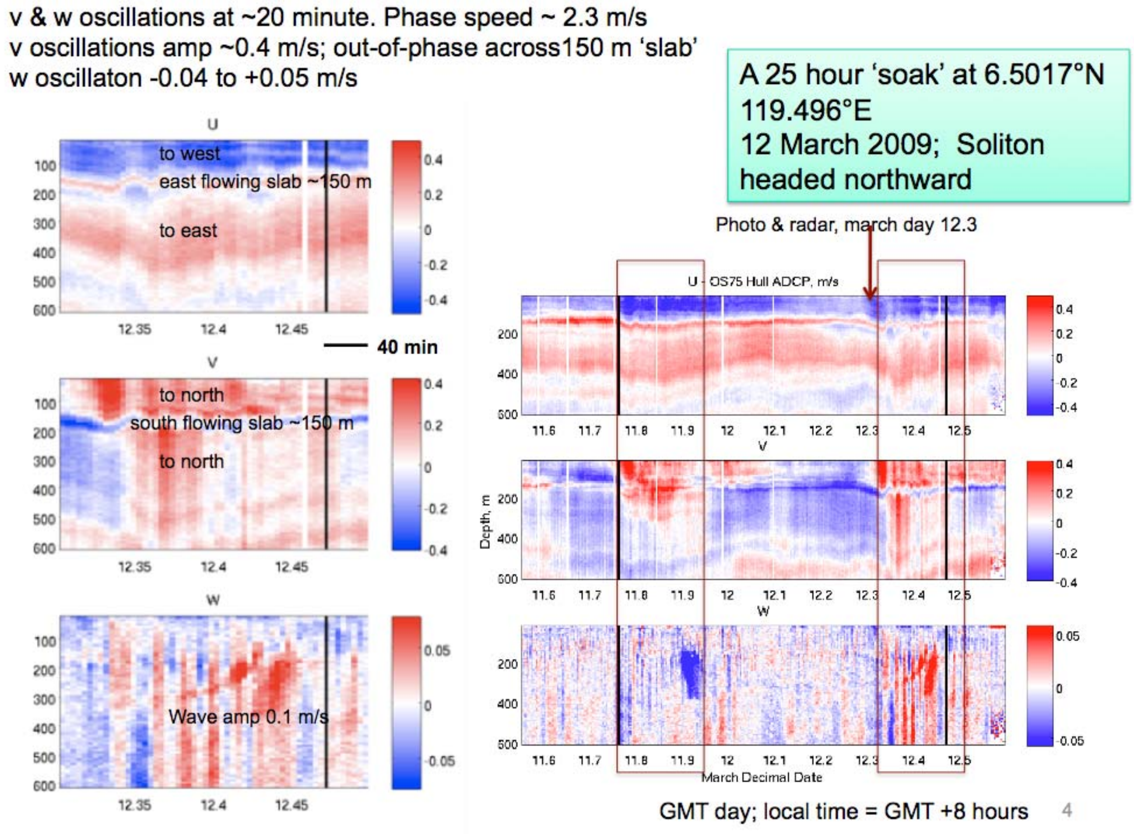


Figure 9. Currents for the upper 500 m during the 25 hour CTD station 'soak' at 6.5017°N 119.496°E, 12 March 2009; Soliton headed northward. The zonal, u, meridional, v, and vertical, w, speeds in m/sec are shown for the duration of our occupation (right panel). The two red boxes in the right panel show the timing of the passage of two soliton packets. A blow up of the 2nd and stronger passage is shown in the left panel. Black lines (right panel) mark the beginning times for casts, the one at 11.75 GMT (station 71) being the beginning of the soak, and at 12.45 GMT (Station 72) is the post-soak full cast. The x-axis is time in day, decimal GMT. The data are 5-minute averages and the hull mounted ADCP OS75 was in broadband mode, bin size of 8m. The first wave at 11.8 was accompanied by radar observations of a wave passing the ship; the second wave at ~12.35GMT photo in shown in figure 8.

During passage of the Soliton u (zonal, + is eastward) and v (meridional, + is northward) flow indicate a marked change in character near 150 m. The v & w (vertical flow, + is upward) values exhibit ~20 minute oscillations (Figure 9), in contrast to a more steady u flow. The v oscillations amp ~0.4 m/s that is out-of-phase across the 150 m 'slab' of weak meridional flow. The singular behavior of the 150 m slab is observed throughout the southern Sulu Sea, and may not be directly associated with the Soliton activity. The w oscillations -0.04 to +0.05 m/s. The large negative w velocity at 11.9 and similar positive w velocity at ~12.45 are associated with the diurnal vertical movement of scatterers in the water column, rather than water movement. These large vertical velocities occur at the same time as changes in the depth of strong echo amplitudes, between 200 and 400m, and are seen everyday at the same time.

We played ‘hopscotch’ with the northward heading soliton as we obtained CTD/LADCP stations while headed northward along 119.5°E. The soliton phase speed ~ 2.3 m/s. The soliton movements during the RIOP09 relative to the ship position are being investigated by Chris Jackson.

6. Other

- Rypina, I., L.J. Pratt, J. Pullen, J. Levin, and A.L. Gordon, 2009: Chaotic advection in an archipelago, J. Phys. Oceanogr. Submitted

- A session at the AGU OS in Portland OR in Feb 2010 ***Oceanography of Archipelagos*** Conveners: Gordon, Arnold L., Lamont-Doherty Earth Observatory/ Columbia; Pullen, Julie, Stevens Institute of Technology.

- In addition: there is collaborative work underway in which the following are 1st author: Pratt, Sprintall, Han, Pullen.

IMPACT/APPLICATIONS

The PhilEx cruises provide information for addressing the PhilEx objectives, by resolving the stratification and circulation patterns inder varied forcing conditions, within the complex topography of the Phillipine Seas. The resultant numerical model, honed by observations, and the enhanced understanding of the oceanography of the Philippine waters to be produced by the PhilEx program will have a multitude of applications in managing marine resources and the marine environment of the Philippines and other archipeligos, as well as for issues of marine safety and prediction of marine pollution dispersion.

TRANSITIONS

None

RELATED PROJECTS

None

REFERENCES

None

PUBLICATIONS

Han, W., A.M. Moore, J. Levin, B. Zhang, H.G. Arango, E. Curchitser, E. Di Lorenzo, A.L. Gordon, and J. Lin, 2009: Seasonal surface ocean circulation and dynamics in the Philippine Archipelago region during 2004–2008, *Dyn. Atmos. Oceans*, 47, 114-137.

PATENTS

None